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Energetic and exergetic investigation of novel multi-flash geothermal systems integrated with electrolyzers

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HIGHLIGHTS

- Comparative study of multi-flash geothermal integrated with electrolyzer.
- Thermodynamic analysis of systems through energy and exergy.
- Performance assessment of systems through energy and exergy efficiencies.

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ABSTRACT

In this paper, a comparative energetic and exergetic study is conducted to analyze novel multi-flash (single to quintuple) geothermal power generating systems which are newly integrated with electrolyzers for hydrogen production. The effects of increasing the number of flashing from one to five for the system on its performance are carefully studied for practical applications. In addition, parametric studies are undertaken to investigate the effects of varying several operating conditions on the performance of the integrated multi-flash systems. The results show that increasing ambient temperature results in smaller exergy destruction rates and higher overall exergy efficiencies. Furthermore, the quintuple-flash system integrated with electrolyzer provides the largest power output and the highest energy and exergy efficiencies among the systems considered. The power generation, hydrogen production rate and overall energy and exergy efficiencies of the quintuple flash integrated system are found to be varying from 6.8 kW to 112.9 kW, 2.6 L s^{-1} to 44.21 L s^{-1}, 2.8%–4.6%, and 46.5%–53.4%, respectively, by increasing the geothermal source temperature.

1. Introduction

Increasing energy and environment related concerns over the years have attracted attention for better design, analysis and assessment of power generating systems. This has recently brought attention to integrated multigeneration systems. In this regard, developing such systems, especially with renewable energy sources, offers multiple benefits [1,2].

Geothermal energy is considered a clean and reliable renewable energy source and offers a range of advantages from being environmentally benign to sustainable [3,4]. Geothermal heat is essentially stored in the Earth's crust within the rocks and fluids. It is this heat which provides the mode for electricity generation or for direct use [5–8]. Geothermal energy can be used for a large variety of applications, such as electricity generation, heating, cooling, industrial drying, fermentation, distillation and desalination depending on the temperature of the source [9]. Geothermal sources are classified into three categories which are (a) high temperature sources (above 150 °C), (b) moderate temperature sources (90 °C–150 °C) and (c) low temperature sources (below 90 °C) [10]. High-temperature geothermal sources are most suitable for large-scale power generation, medium temperature sources are suitable for power generation as well as heating or cooling production, and low temperature sources are recommended for direct heating. Geothermal energy can be used to produce electricity using three major types of power plants which are dry steam plants, flash-steam plants and binary-cycle plants. The binary and combined flash/binary plants are considered relatively recent designs in the area of geothermal power generation [11]. The use of these power plants is also governed by geothermal source temperature. For high temperature geothermal source it is best to use single- and double-flash power plants [8]. Yari [12] conducted a case study where he compared some geothermal systems and

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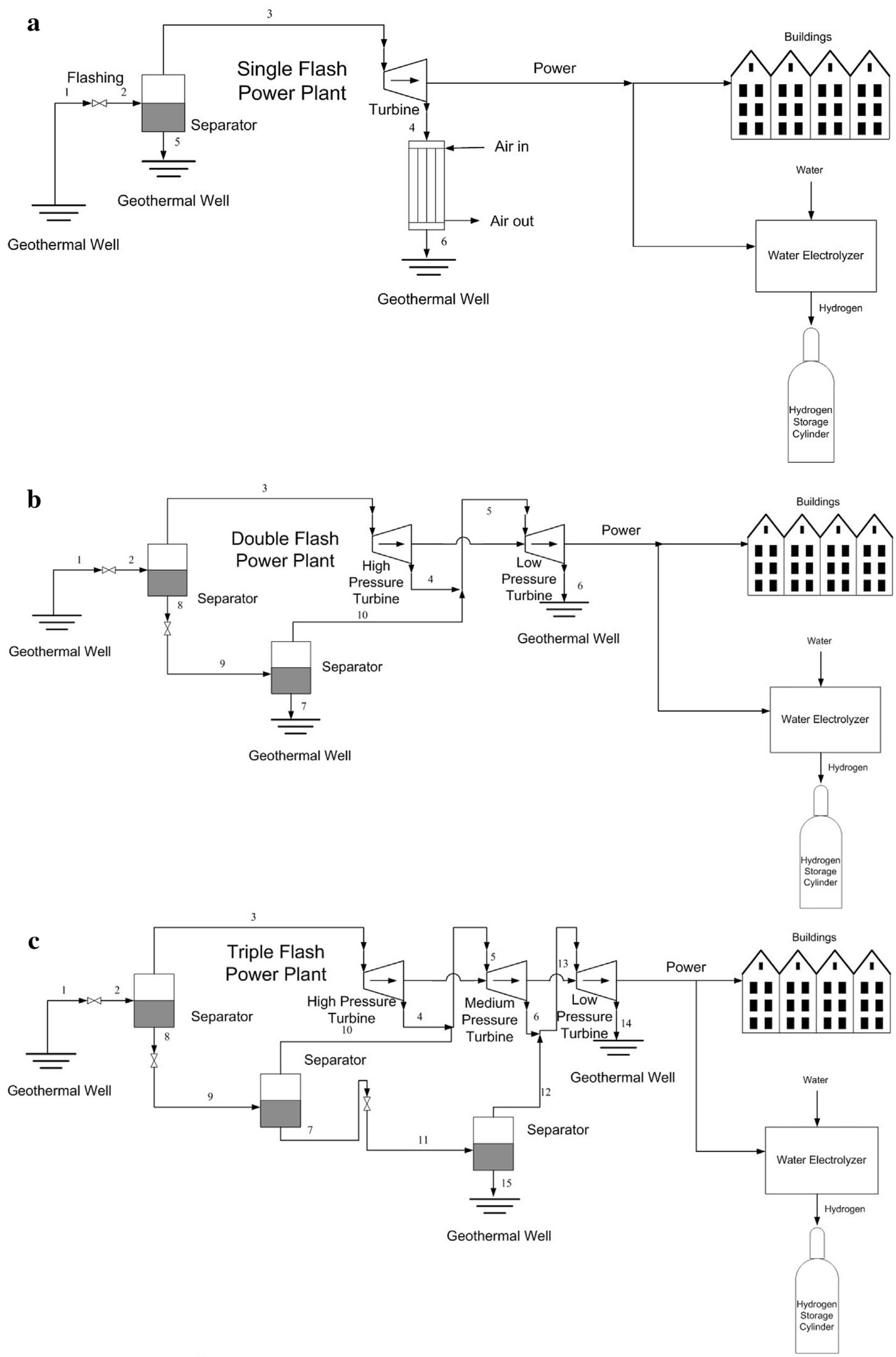
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Power Plant
Flashing
Separator
Turbine
Power
Buildings
Air in
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Geothermal Well
Geothermal Well
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b
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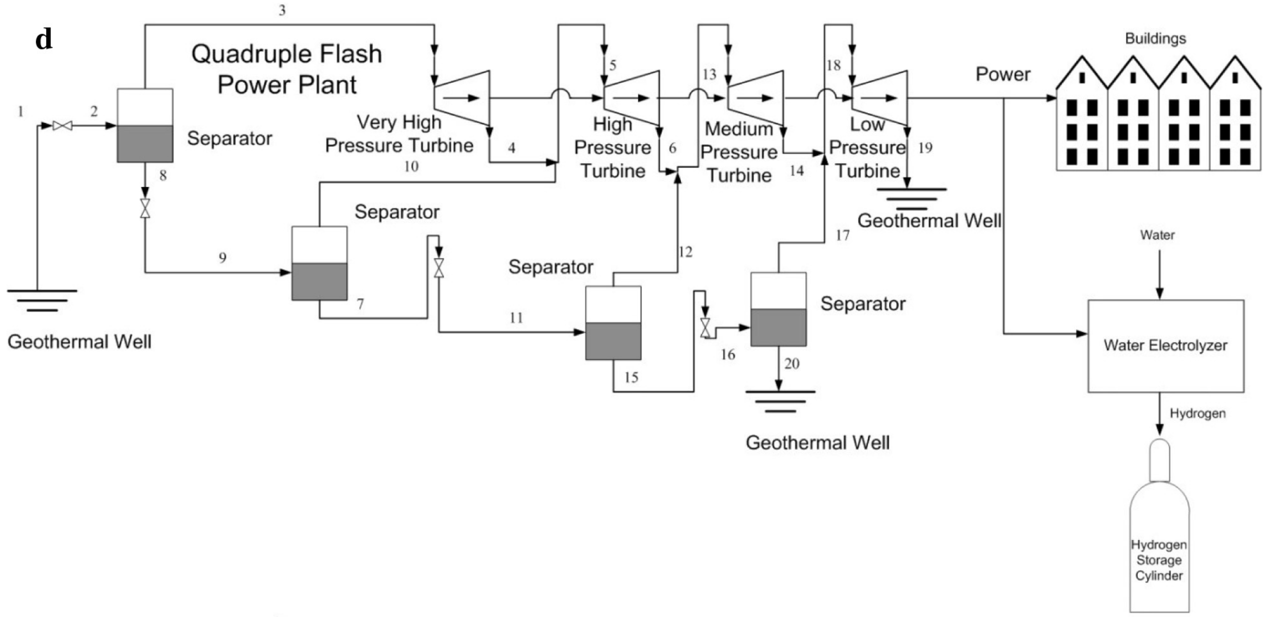

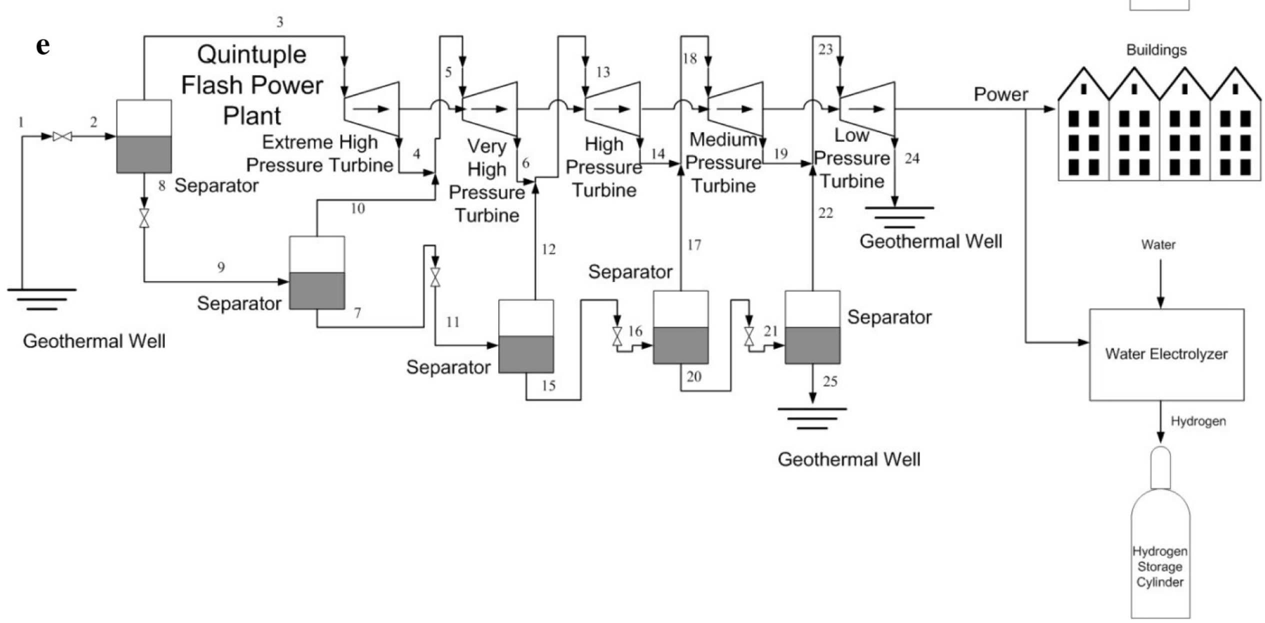

Fig. 1. a. Schematic diagrams of single flash integrated with electrolyzer. b. double flash integrated with electrolyzer. c. triple flash integrated with electrolyzer. d. quadruple flash integrated with electrolyzer. e. quintuple flash integrated with electrolyzer.

found that double-flash system provides higher power output and better efficiency as compared to single flash system. Another study conducted by Bodvardson and Eggers [13] showed that double flash system utilizes 15% more of available exergy as compared to single flash system. In order to develop the systems further for better efficiency and effectiveness, we conduct a comparative analysis of multi-flash systems from the energy and exergy perspectives.

The most common method of producing hydrogen is through water electrolysis which is mature and commercially viable. Apart from geothermal, hydrogen is another energy carrier which has the capabilities of working as an alternative fuel and can carry energy in an environmentally benign and sustainable manner as suggested by studies carried out by several researchers [e.g., Refs. [14–16]].

In this study, we first-time ever consider single-, double-, triple-, quadruple- and quintuple-flash geothermal power generating systems and integrate them with electrolyzers for hydrogen production. We analyze these systems thermodynamically through energy and exergy and study their energy and exergy efficiencies for comparison purposes. Parametric studies are also carried out to investigate the effect of varying ambient temperature, geothermal source temperature and geothermal mass flow rate on the power produced by the plant, power supplied to the building, rate of hydrogen production and energy and exergy efficiencies of the overall system. The results of each of the five systems are compared to show how the system performance is enhanced by increasing the number of flashing.

2. System description

In this paper, we investigate five integrated systems, namely single-, double-, triple-, quadruple- and quintuple-flash geothermal power generating systems integrated with electrolyzers for hydrogen production, as illustrated in Fig. 1a–e. For illustration purposes, the description of double flash geothermal system

integrated with electrolyzer is given below. In the double flash power plant, geothermal stream enters the expansion valve at state 1. Here, pressure of the stream is reduced which later enters the first flashing chamber at state 2. In the flashing chamber, steam is extracted from the upper half at state 3 and saturated mixture is allowed to leave from the bottom half at state 8. The steam extracted at state 3 enters the high pressure turbine (HPT) and expands to state 4 to produce power. However, stream from state 8 enters the second expansion valve to enter the second flashing chamber at reduced pressure (state 9). In the second flashing chamber, steam is extracted at state 10 which then mixes with stream coming from state 4 to enter the low pressure turbine. The geothermal liquid exiting from bottom half of the second flash chamber is reinjected to the well at state 7. In the low pressure turbine (LPT), steam from state 5 expands to state 6 to produce power. Power produced by HPT and LPT is then supplied to the building (20%) and the electrolyzer (80%). The geothermal water leaving LPT at state 6 is also reinjected to the well. The power supplied to the electrolyzer is utilized to break water bond in order to produce hydrogen. Hydrogen produced is stored in the tanks for later use. Other flash systems work in the same manner the only difference is that they either have lesser or greater number of flashing chambers.

3. Energy and exergy analyses

Energy and exergy analyses of each of the five systems are carried out to study the effect of varying operating conditions on the performance of each of these systems. The results obtained are then compared to show how performance of the integrated system varies with increase in the number of flashing units. For illustration purposes, energy and exergy analyses of a double flash system integrated with electrolyzer are provided below. The software developed by Klein [17] Engineering Equation Solver (EES) is used to obtain thermodynamic values and to solve for energy and exergy balance equations.

3.1. Double flash power plant

The power produced by the turbines is calculated using

$$\dot{W}_{\mathrm{turb}} = \dot{m}_3(h_3 - h_4) + \dot{m}_5(h_5 - h_6) \tag{1}$$

where $\dot{W}_{\mathrm{turb}}$ represents power produced by turbine(s), and $\dot{m}$ and h represent mass flow rate of geothermal water and specific enthalpy of geothermal water, respectively.

The exergetic content at state 1 is defined as

$$\dot{E}x_1 = \dot{m}_1((h_1 - h_0) - T_0(s_1 - s_0)) \tag{2}$$

where $\dot{E}x_1$ represents exergy rate of geothermal water at state 1, $\dot{m}$ represents mass flow rate of geothermal water, h represents specific enthalpy of geothermal water and s represents specific entropy of geothermal water.

The same formulation is used to calculate exergy rate at each state.

In order to have the correct model, parasitic losses are also considered. The percentage of parasitic losses can be considered to be 20% as suggested in the recent literature [4].

$$\dot{W}_{\mathrm{parasitic}} = 0.2\left(\dot{W}_{\mathrm{turb}}\right) \tag{3}$$

where $\dot{W}_{\mathrm{parasitic}}$ represents parasitic losses occurring in the system.

The actual net power that can be obtained from the double flash power plant running on geothermal water is expressed as

$$\dot{W}_{\mathrm{net_{geo}}} = \dot{W}_{\mathrm{turb}} - \dot{W}_{\mathrm{parasitic}} \tag{4}$$

where $\dot{W}_{\mathrm{net_{geo}}}$ represents net power produced by the geothermal power plant.

It is assumed that 20% of the power is supplied to the building in order to provide adequate power for the operation of the power plant and is calculated as

$$\dot{W}_{\mathrm{bld}} = 0.2 \times \dot{W}_{\mathrm{net_{geo}}} \tag{5}$$

where $\dot{W}_{\mathrm{bld}}$ represents power supplied to the building.

The exergy destruction rate of double flash system and integrated system is found using

$$\dot{E}x_{\mathrm{dest,f}} = \dot{E}x_1 - \dot{E}x_6 - \dot{E}x_7 - \dot{W}_{\mathrm{net_{geo}}} \tag{6}$$

$$\dot{E}x_{\mathrm{dest,ov}} = \dot{E}x_1 - \dot{E}x_6 - \dot{E}x_7 - \dot{W}_{\mathrm{bld}} - \dot{E}x_{H_2} \tag{7}$$

where $\dot{E}x_{\mathrm{dest,f}}$ represents exergy destruction rate of flash power plant and $\dot{E}x_{\mathrm{dest,ov}}$ represents overall exergy destruction rate of the integrated system.

3.2. Electrolyzer

$$\eta_{\mathrm{electrolyzer}} = \frac{\dot{m}_{H_2} \times \mathrm{HHV}}{\dot{W}_{\mathrm{electrolyzer}}} \tag{8}$$

where electrolyzer efficiency is considered to be 56%, power supplied to the electrolyzer is $\dot{W}_{\mathrm{electrolyzer}} = 0.8 \times \dot{W}_{\mathrm{net_{geo}}}$, $\dot{m}_{H_2}$ represents mass flow rate of hydrogen and HHV represents higher heating value of hydrogen.

The exergetic content of hydrogen is obtained by using

$$\dot{E}x_{H_2} = \dot{m}_{H_2}\left[ex_{H_2,ch} + ex_{H_2,ph}\right] \tag{9}$$

where

$$ex_{H_2,ch} = \frac{235.153 \times 1000}{MW_{H_2}}$$

$$ex_{H_2,ph} = \left[(h_{H_2} - h_0) - T_0(s_{H_2} - s_0)\right]$$

here, $ex_{H_2,ch}$ represents chemical exergy content of hydrogen, MW_{H_2} represents molecular weight of hydrogen, $ex_{H_2,ph}$ represents physical exergy content of hydrogen, and the number 235.153 represents exergy content of the hydrogen in MJ mol^{-1}.

The overall energy and exergy efficiencies of the integrated system are defined as

$$\eta_{\mathrm{en,sys}} = \left[\frac{\dot{W}_{\mathrm{bld}} + \dot{m}_{H_2}h_{H_2}}{\dot{m}_1h_1 - (\dot{m}_6h_6 + \dot{m}_7h_7)}\right] \tag{10}$$

$$\eta_{\mathrm{ex,sys}} = \left[\frac{\dot{W}_{\mathrm{bld}} + \dot{E}x_{H_2}}{\dot{E}x_1 - \left(\dot{E}x_6 + \dot{E}x_7\right)}\right] \tag{11}$$

where $\eta_{\mathrm{en,sys}}$ and $\eta_{\mathrm{en,sys}}$ represent energy and exergy efficiencies of the system, respectively.

4. Results and discussion

In this paper, we have conducted detailed energy and exergy analyses of multi-flash systems integrated with electrolyzer for

Table 1
Assumptions for single flash system.

Variables	Values
T_1	430 K–530 K
P_1	3000 kPa
$\dot{m}_1$	0.5 kg s^{-1} to 1.5 kg s^{-1}
P_2	667 kPa
T_6	303.1 K

Table 3
Assumptions for triple flash system.

Variables	Values
T_1	430 K–530 K
P_1	3000 kPa
$\dot{m}_1$	0.5 kg^{-1}–1.5 kg^{-1}
P_2	667 kPa
P_4	400 kPa
P_6	300 kPa
T_{16}	303.1 K

power and hydrogen production. Performances of each of the five integrated systems are compared to see how system performance gets enhanced when numbers of flashes are increased. Parametric studies are conducted to show the effect of variation in ambient temperature, geothermal source temperature and geothermal mass flow rate on the power production rate, hydrogen production rate, and energy and exergy efficiencies of the integrated systems. The present geothermal flash systems are, in this regard, modeled by some data and aspects provided in Ref. [18]. The efficiencies of turbine and electrolyzer are taken as 80% and 56%, respectively. However, for ambient conditions, T_0 and P_0 are assumed to be 298 K and 100 kPa, respectively. Tables 1–5 tabulate the assumptions which are made to model the geothermal flash systems. The temperature of the stream exiting the condenser is taken to be 303.1 K in each of the five flash systems for fair comparison of results.

4.1. Effect of ambient temperature

It is important to note that the performance of any system is dependent considerably on the ambient conditions. The variations in such conditions may enhance the performance of some systems and may degrade some others. Fig. 2a illustrates variation of exergy destruction rate in the flash system with an increase of ambient temperature. It is obtained that for each particular flash system, exergy destruction rate decreases with rise in ambient temperature. For single, double, triple, quadruple and quintuple flash systems exergy destruction rate is found to be decreasing from 125.4 kW to 108.2 kW, 145.6 kW to 124.1 kW, 148.7 kW to 125.1 kW, 146.9 kW to 120.6 kW, and 107.8 kW to 77.35 kW, respectively with rise in ambient temperature from 290 K to 310 K. This behavior is obtained because geothermal systems work at high temperature and by increasing the ambient temperature, the temperature difference between geothermal stream and ambient condition decreases, and hence, exergy destruction rate of the system decreases. Fig. 2b shows the variation of exergy destruction rate of the overall integrated systems with rise in ambient temperature. The exergy destruction rate of all five integrated systems, namely single flash integrated with electrolyzer, double flash integrated with electrolyzer, triple flash integrated with electrolyzer, quadruple flash integrated with electrolyzer, and quintuple flash integrated with electrolyzer is found to be decreasing from 125.9 kW to 108.7 kW, 146.4 kW to 125 kW, 150 kW to 126.4 kW, 149.1 kW to 122.8 kW, and 113.3 kW–82.87 kW, respectively with rise in ambient temperature. It is interesting to note that the exergy destruction rates of both flash system and integrated system increase with multi-flash up to triple flash point, after which the exergy destruction rate starts decreasing again at a constant ambient temperature. The results show that though increasing number of flash will not be seen viable if studies are conducted up to triple flash system only but once quintuple flash system is modeled the scenario changes. The quintuple flash system gives the lowest exergy destruction rate as compared to other multi-flash systems. The variations of exergy efficiency of the integrated system with increasing ambient temperature are also studied as shown in Fig. 3. The results show that with increase in number of flashing, the exergetic efficiency of the integrated system increases. For single flash integrated with electrolyzer, double flash integrated with electrolyzer, triple flash integrated with electrolyzer, quadruple flash integrated with electrolyzer, and quintuple flash integrated with electrolyzer exergy efficiency is found to be varying from 6.1% to 7.1%, 8.6% to 10%, 12.8% to 14.8%, 19.8% to 23.1%, and 44.4% to 52.2%, respectively with increase in ambient temperature. An increase in exergy efficiency with increase in ambient temperature and number of flashing confirms that increasing number of flash in an integrated system will indeed enhance the performance of the system.

4.2. Effect of geothermal source temperature

As discussed in introduction, geothermal source temperature determines whether geothermal stream is capable of generating power or not. Study shows that increase in geothermal source temperature results in the curve behavior of the power production line as shown in Fig. 4. The amount of power produced by single flash, double flash, triple flash, quadruple flash, and quintuple flash vary from 0 kW to 197.8 kW, 0.9 kW to 229.5 kW, 3 kW to 272.7 kW, 8.4 kW to 342.5 kW, and 33.9 kW to 564.5 kW, respectively with increase in T_1 from 430 K to 530 K. This behavior is noticed because increase in T_1 results in a higher energy content of the incoming geothermal stream. Also, as number of flashings increase, larger amount of energy is being recovered from the geothermal stream rather than dumping stream with high energy content into the geothermal well. Fig. 5a illustrates the variation in rate of hydrogen produced by the integrated systems with increase in T_1. Results show that rate of hydrogen produced by single flash integrated with electrolyzer, double flash integrated with electrolyzer, triple

Table 2
Assumptions for double flash system.

Variables	Values
T_1	430 K–530 K
P_1	3000 kPa
$\dot{m}_1$	0.5 kg s^{-1}–1.5 kg s^{-1}
P_2	667 kPa
P_4	400 kPa
T_6	303.1 K

Table 4
Assumptions for quadruple flash system.

Variables	Values
T_1	430 K–530 K
P_1	3000 kPa
$\dot{m}_1$	0.5 kg s^{-1}–1.5 kg s^{-1}
P_2	667 kPa
P_4	400 kPa
P_6	300 kPa
P_{14}	200 kPa
T_{21}	303.1 K

Table 5
Assumptions for quintuple flash system.

Variables	Values
T_1	430 K–530 K
P_1	3000 kPa
$\dot{m}_1$	0.5 kg s^{-1}–1.5 kg s^{-1}
P_2	667 kPa
P_4	400 kPa
P_6	300 kPa
P_{14}	200 kPa
P_{19}	100 kPa
T_{26}	303.1 K

flash integrated with electrolyzer, quadruple flash integrated with electrolyzer, and quintuple flash integrated with electrolyzer vary from 0 L s^{-1} to 15.49 L s^{-1}, 0.1 L s^{-1} to 17.98 L s^{-1}, 0.2 L s^{-1} to 21.36 L s^{-1}, 0.7 L s^{-1} to 26.8 L s^{-1}, and 2.6 L s^{-1} to 44.21 L s^{-1}, respectively with increase in T_1. This trend is observed because as the amount of power produced by the power plant increases the amount of electrical work supplied to the electrolyzer increases and as a result of this the hydrogen production rate increases. Increase in T_1 also affects the amount of power supplied to the building as shown in Fig. 5b. The amount of power supplied to the building by single flash, double flash, triple flash, quadruple flash, and quintuple flash systems vary from 0 kW to 39.55 kW, 0.2 kW to 45.9 kW, 0.6 kW to 54.5 kW, 1.7 kW to 68.49 kW, and 6.8 kW to 112.9 kW, respectively with increase in T_1. Increase in power supplied to the

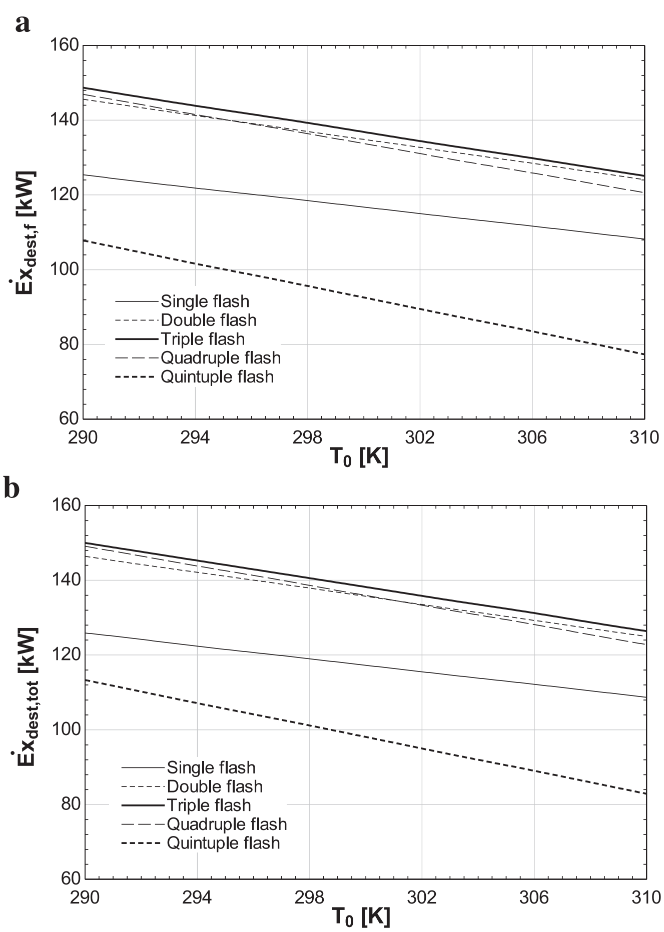

Fig. 2. a. Effect of rise in ambient temperature on exergy destruction rate of geothermal flash systems. b. Effect of rise in ambient temperature on total exergy destruction rate.

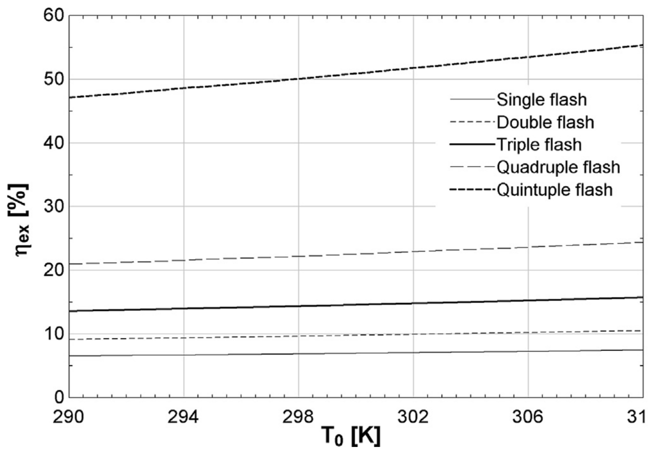

Fig. 3. Effects of rise in ambient temperatures on exergetic efficiency of the overall system.

building with increase in number of flashings is observed because power supplied to the building is directly related to the amount of power produced by the geothermal system. Fig. 6a displays the variation in exergy destruction rate in geothermal multi-flash power plants with increase in T_1. It is seen that the exergy destruction rate in single flash, double flash, triple flash, quadruple flash, and quintuple flash systems vary from 1.8 kW to 749.6 kW, 20.53 kW to 769 kW, 31.3 kW to 725.4 kW, 41.13 kW to 655.3 kW, and 34.7 kW to 432.6 kW, respectively with increase in T_1. It is interesting to see that for low temperature geothermal source, the exergy destruction rate is lowest in single flash but as T_1 increases the exergy destruction rate in single flash becomes the highest. Moreover, with increase in number of flashings, exergy destruction rate increases till double flash system and then starts dropping again. For high temperature geothermal source, it is observed that quintuple flash system has lowest exergy destruction rate hence, indicating that increase in number of flash helps reducing rate of exergy destructed by the system. Fig. 6b exhibits the variations of exergy destruction rate of the integrated systems with T_1. As can be seen in this figure, the exergy destruction rate in single flash integrated with electrolyzer, double flash integrated with electrolyzer, triple flash integrated with electrolyzer, quadruple flash integrated with electrolyzer, and quintuple flash integrated with electrolyzer fluctuate from 1.8 kW to 761 kW, 20.6 kW to 782.2 kW, 31.5 kW to 741.1 kW, 41.6 kW to 674.9 kW, and 36.7 kW to 465.1 kW,

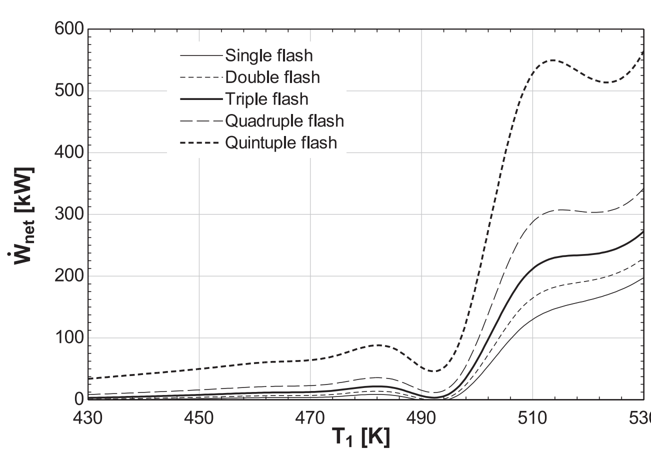

Fig. 4. Effect of increase in geothermal source temperature on power generated.

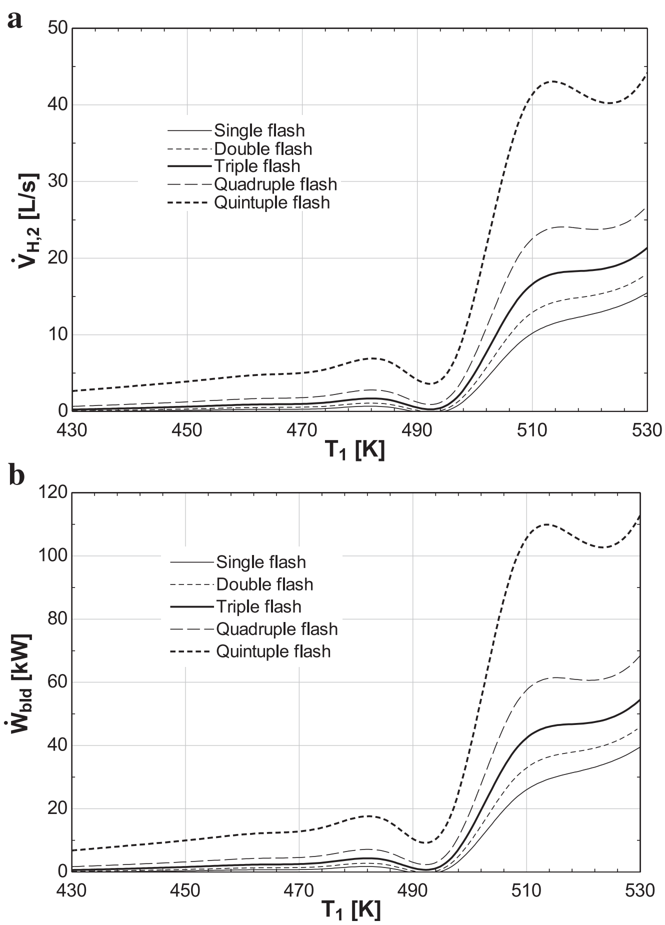

Fig. 5. a. Effects of increase in geothermal source temperature on rate of hydrogen produced. b. Effect of increase in geothermal source temperature on power supplied to the building.

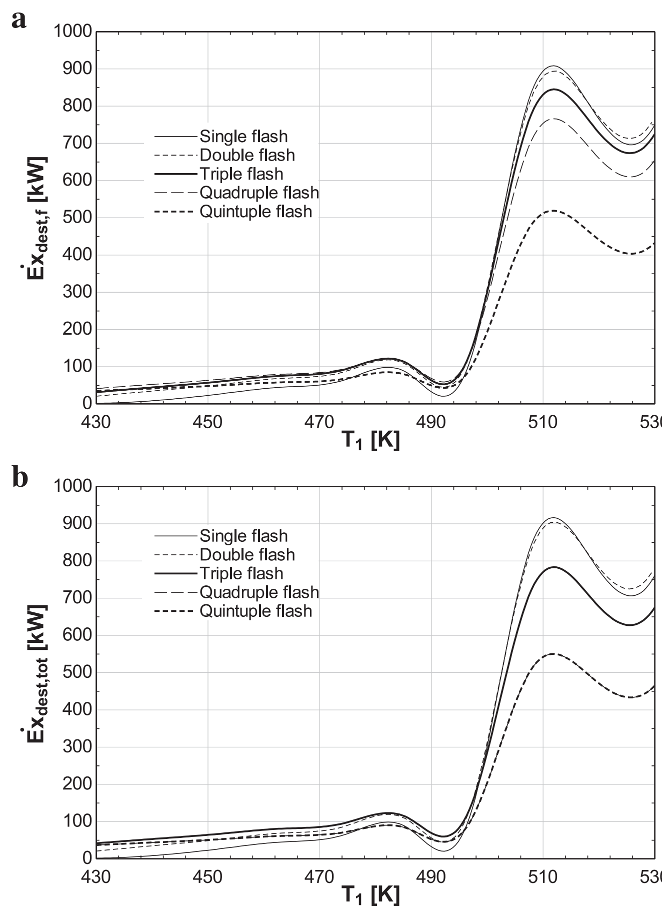

Fig. 6. a. Effects of increase in geothermal source temperature on exergy destruction rate of geothermal flash system. b. Effect of increase in geothermal source temperature on total exergy destruction rate.

respectively with increase in T_1. Following the same trend as that of exergy destruction rate in multi-flash systems, the exergy destruction rate is lowest in single flash integrated with electrolyzer for low T_1, but for a high T_1, the exergy destruction rate is lowest in quintuple flash integrated with electrolyzer system. Fig. 7a summarizes the performance of the multi-flash integrated systems in terms of energetic efficiency of the overall system. The overall energetic efficiency of the single flash integrated with electrolyzer, double flash integrated with electrolyzer, triple flash integrated with electrolyzer, quadruple flash integrated with electrolyzer, and quintuple flash integrated with electrolyzer vary from 0.4% to 1.6%, 0.3% to 1.9%, 0.6% to 2.2%, 1% to 2.8%, and 2.8% to 4.6%, respectively with increase in T_1. In addition to this, variation in exergetic efficiency of the overall system with increase in T_1 is displayed in Fig. 7b. The overall exergetic efficiency of the single flash integrated with electrolyzer, double flash integrated with electrolyzer, triple flash integrated with electrolyzer, quadruple flash integrated with electrolyzer, and quintuple flash integrated with electrolyzer fluctuate from 0.1% to 19.7%, 4% to 21.7%, 8.4% to 25.8%, 15.9% to 32.4%, and 46.5% to 53.4%, respectively with increase in T_1. Increase in both energetic and exergetic efficiencies of the overall system with increase in T_1 are observed because increase in T_1 results in higher power production and rate of hydrogen production. As the system output increases, the performance of the system enhances, and this enhancement in performance is shown in terms of higher energetic and exergetic efficiencies. As total exergy destruction rate decreases from single flash to quintuple flash integrated system, the exergetic performance of the system enhances from single flash to quintuple flash integrated system for a specific T_1. Another interesting point to note is that from Figs. 4–7, the values change in a wavy manner; and such behavior is noticed because for a specific pressure the change in enthalpy takes place with changes in temperature. As an example, the enthalpy of water shoot ups when it goes from saturated vapor state to superheated vapor, working on the same concept when temperatures go beyond certain limit the enthalpy values either shoots up or shoots down and therefore presenting a wave-like trend. This fluctuating performance is essential to see where the local minimum and local maximum points are for a given temperature range.

4.3. Effect of geothermal mass flow rate

The geothermal mass flow rate is another important parameter which affects the performance of the geothermal water based systems. It can be seen in Fig. 8 that increases in $\dot{m}_1$ results in higher amount of power produced by multi-flash systems. The amount of power produced by single flash, double flash, triple flash, quadruple flash, and quintuple flash vary from 4.4 kW to 13.2 kW, 7.3 kW to 22 kW, 11.7 kW to 35.1 kW, 19.5 kW to 58.5 kW, and 48 kW to 144 kW, respectively with increase in $\dot{m}_1$ from 0.5 kg s^{-1} to 1.5 kg s^{-1}. This behavior is observed because for specific geothermal source temperature and pressure, increase in $\dot{m}_1$ results in higher amount of steam passing through the turbines and therefore, increasing the amount of power produced by the system. Moreover,

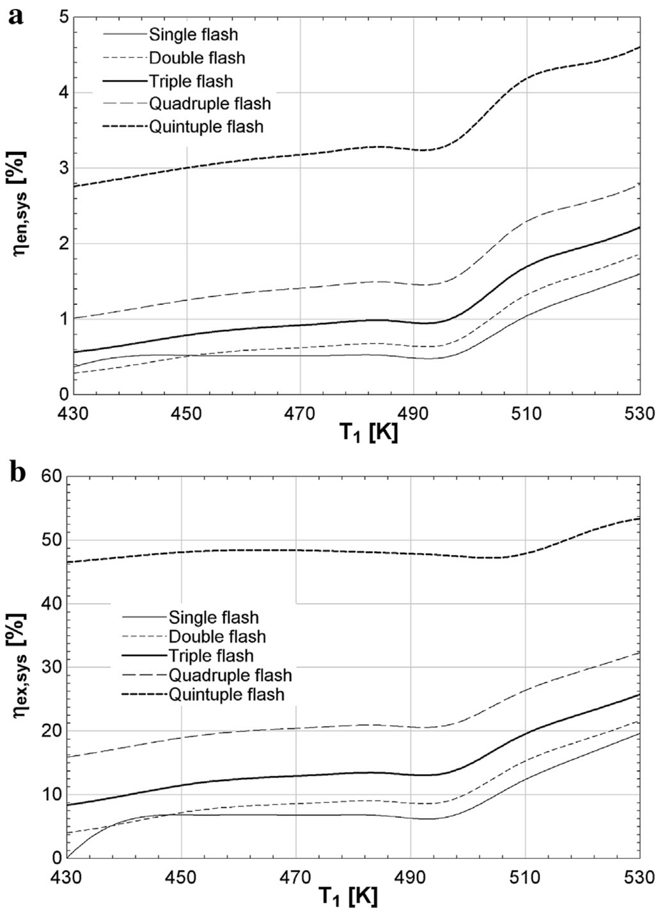

Fig. 7. a. Effects of increase in geothermal source temperature on energetic efficiency of the overall system. b. Effect of increase in geothermal source temperature on exergetic efficiency of the overall system.

the amount of power produced is found to be increasing with increase in number of flashes. The rate of hydrogen produced is also found to be increasing with increase in $\dot{m}_1$ as seen in Fig. 9a. The results show that rate of hydrogen produced by single flash integrated with electrolyzer, double flash integrated with electrolyzer, triple flash integrated with electrolyzer, quadruple flash integrated with electrolyzer, and quintuple flash integrated with electrolyzer

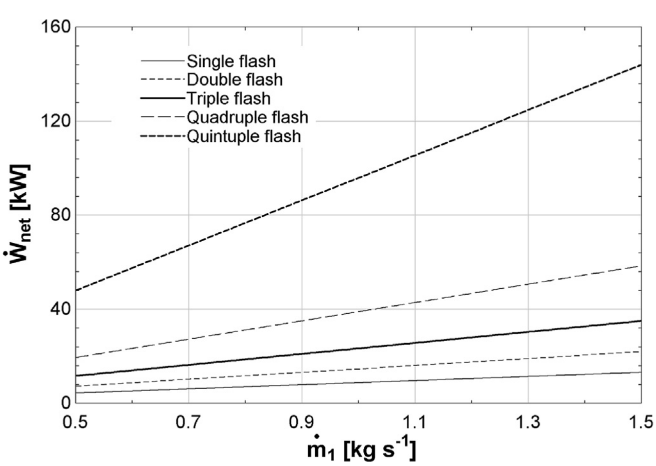

Fig. 8. Effects of increase in geothermal source mass flow rate on net power generated.

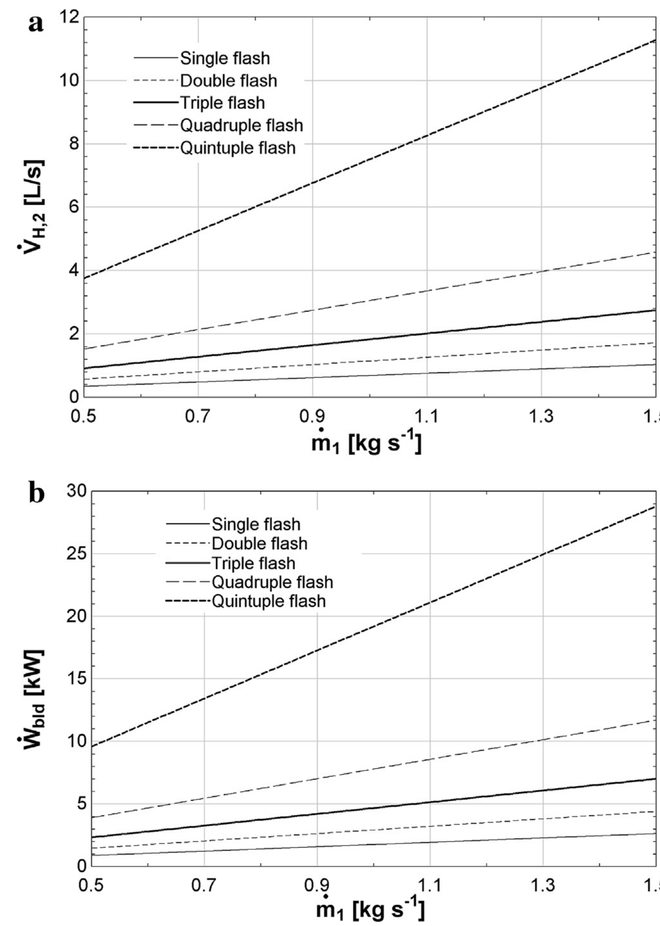

Fig. 9. a. Effects of increase in geothermal source mass flow rate on rate of hydrogen produced. b. Effect of increase in geothermal source mass flow rate on power supplied to the building.

vary from 0.3 L s^{-1} to 1 L s^{-1}, 0.6 L s^{-1} to 1.7 L s^{-1}, 0.9 L s^{-1} to 2.7 L s^{-1}, 1.5 L s^{-1} to 4.6 L s^{-1}, and 3.8 L s^{-1} to 11.3 L s^{-1}, respectively with increase in $\dot{m}_1$. Similarly the amount of power supplied to the building increases with increase in $\dot{m}_1$ as shown in Fig. 9b. The amount of power supplied to the building by single flash, double flash, triple flash, quadruple flash, and quintuple flash vary from 0.9 kW to 2.6 kW, 1.5 kW to 4.4 kW, 2.3 kW to 7.0 kW, 3.9 kW to 11.7 kW, and 9.6 kW to 28.8 kW, respectively with increase in $\dot{m}_1$. This rise in hydrogen production rate and amount of power supplied with increase in $\dot{m}_1$ is directly related to the rise in amount of power generated by multi-flash systems with increase in $\dot{m}_1$. Fig. 10a displays the results of increase in $\dot{m}_1$ on exergy destruction rate in multi-flash systems. Exergy destruction rate in single flash, double flash, triple flash, quadruple flash, and quintuple flash vary from 59.2 kW to 177.5 kW, 68.4 kW to 205.3 kW, 69.5 kW to 208.6 kW, 68.1 kW to 204.2 kW, and 47.7 kW to 143.1 kW, respectively with increase in $\dot{m}_1$. Moreover, increase in $\dot{m}_1$ also affects the total exergy destruction rate of the system as shown in Fig. 10b. The total exergy destruction rate in single flash integrated with electrolyzer, double flash integrated with electrolyzer, triple flash integrated with electrolyzer, quadruple flash integrated with electrolyzer, and quintuple flash integrated with electrolyzer vary from 59.4 kW to 178.3 kW, 68.8 kW to 206.5 kW, 70.2 kW to 210.6 kW, 69.2 kW to 207.6 kW, and 50.4 kW to 151.3 kW, respectively with increase in $\dot{m}_1$. It is observed that increase in $\dot{m}_1$ forces increase in exergy destruction rate from single flash to triple flash systems, but after triple flash system exergy destruction rate

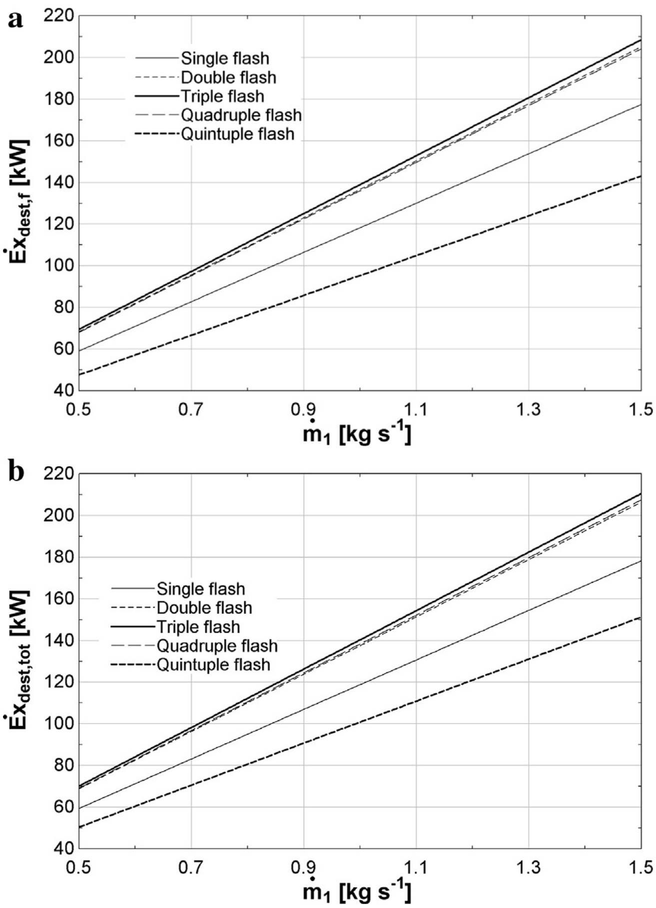

Fig. 10. a. Effects of increase in geothermal source mass flow rate on exergy destruction rate of geothermal flash systems. b. Effect of increase in geothermal source mass flow rate on total exergy destruction rate.

starts decreasing. The lowest exergy destruction rate is obtained for quintuple flash system, indicating that increase in number of flash after certain point results in lower exergy destruction rate and better performance of the system.

4.4. Results on exergy destruction rates

Fig. 11 helps visualize clearly that which system destructs most amount of exergy for a given operating conditions. As we know that

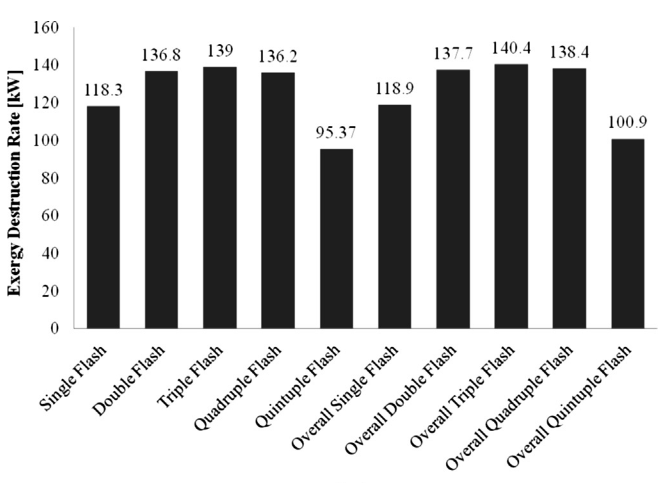

Fig. 11. Exergy destruction rates in the systems.

higher exergy destruction rate denotes worst performance of a system and shows that system can be improved in order to gain more output from the system. Fig. 11 shows that exergy destruction rate in both, only flash systems and flash integrated with electrolyzer systems increase till triple flash systems. After triple flash systems exergy destruction rate starts decreasing. The lowest exergy destruction rate is obtained for the quintuple flash system indicating that quintuple flash system is most efficient from exergy point of view.

5. Conclusions

In this paper, we develop novel multi-flash systems integrated with electrolyzers for power and hydrogen productions, and conduct conceptual and parametric studies to investigate and compare their performances through energy and exergy analyses and efficiency assessments. The ambient temperatures, geothermal source temperatures and geothermal mass flow rates are varied to study their effects on the amounts of power produced, amount of power supplied to the building, rate of hydrogen produced, total exergy destruction in the flash system, total exergy destruction in the integrated system and energy and exergy efficiencies of the overall system. Finally, a bar chart is presented to summarize the exergy destruction rates in the multi-flash systems and the overall integrated systems.

The results show that the best efficiency is obtained for the quintuple flash system. The exergy destruction rates in multi-flash systems and integrated systems are found to be decreasing with an increase in the ambient temperature. Moreover, a rise in the ambient temperature improves the exergetic performance of the integrated system as depicted by exergetic efficiency of the overall system. Increase in the geothermal temperature makes system perform better with having higher power production and rate of hydrogen production. Furthermore, an increase in the geothermal source temperature results in a higher exergy destruction rate in both multi-flash systems and integrated systems. Overall energetic and exergetic efficiencies are observed to be increasing with increase in the geothermal source temperature and number of flashes. Exergy destruction rates in the systems and their components are found to be increasing with increase in geothermal mass flow rate. After comparing the efficiency results it is observed that increase in the number of flashes has positive effect on the performance of the overall system.

Nomenclature

$\dot{E}n$	Energy rate, kW
$\dot{E}x$	Exergy rate, kW
$\dot{m}$	mass flow rate, kg s^{-1}
MW	molecular weight, kg kmol^{-1}
P	pressure, kPa
$\dot{Q}$	heat transfer rate, kW
T	temperature, K
$\dot{W}$	work rate, kW

Greek letters

η	efficiency

Subscripts

ch	chemical
en	energy
ex	exergy
geo	geothermal
H_2	hydrogen
H,2	hydrogen
i	in

o	out
ph	physical
turb	turbine
1–25	state numbers
0	ambient or reference condition

References

[1] I. Dincer, C. Zamfirescu, Int. J. Energy Res. 36 (2012) 1403–1415.
[2] I. Dincer, C. Zamfirescu, Energy 46 (2011) 5–15.
[3] M.T. Balta, I. Dincer, A. Hepbasli, Int. J. Hydrogen Energy 34 (2009) 2925–2939.
[4] M. Kanoglu, I. Dincer, M.A. Rosen, Int. J. Hydrogen Energy 32 (2007) 4250–4257.
5 I. Dincer, M.A. Rosen, EXERGY: Energy, Environment and Sustainable Development, second ed., Elsevier, Oxford, 2013.
[6] M.F. Orhan, I. Dincer, M.A. Rosen, Int. J. Energy Res. 36 (2012) 1388–1394.
[7] L. Ozgener, A. Hepbasli, I. Dincer, Int. J. Energy Res. 29 (2005) 393–408.
[8] A. Alicilar, M. Dogan, M. Guru, Int. J. Energy Res. 19 (1995) 169–179.
[9] C. Coskun, Z. Oktay, I. Dincer, Energy 36 (2011) 6358–6366.
[10] M. Kanoglu, A. Bolatturk, Renew. Energy 33 (2008) 2366–2374.
[11] C. Coskun, Z. Oktay, I. Dincer, Appl. Therm. Eng. 31 (2011) 4074–4082.
[12] M. Yari, Renew. Energy 35 (2010) 112–121.
[13] G. Bodvardson, D.E. Eggers, Geothermics 1 (1972) 93–95.
[14] J. Turner, Int. J. Energy Res. 32 (2008) 379–407.
[15] I. Dincer, Int. J. Energy Res. 31 (2007) 29–55.
[16] S. Aghahosseini, I. Dincer, G.F. Naterer, Int. J. Hydrogen Energy 36 (2011) 2845–2854.
[17] S.A. Klein, F-Chart Software, 2012. www.fChart.com.
[18] T.A.H. Ratlamwala, I. Dincer, Appl. Therm. Eng. 48 (2012) 359–366.